Automatic Generation of Overlays and Offset Values Based on Visiting Vehicle Telemetry and RWS Visuals

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The development of computer software as a tool to generate visual displays has led to an overall expansion of automated computer generated images in the aerospace industry. These visual overlays are generated by combining raw data with pre-existing data on the object or objects being analyzed on the screen. The National Aeronautics and Space Administration (NASA) uses this computer software to generate onscreen overlays when a Visiting Vehicle (VV) is berthing with the International Space Station (ISS). In order for Mission Control Center personnel to be a contributing factor in the VV berthing process, computer software similar to that on the ISS must be readily available on the ground to be used for analysis. In addition, this software must perform engineering calculations and save data for further analysis.

Nomenclature

ARO = Automated Rendezvous Officer
CV = Capture Volume
FRGF = Flight Releasable Grapple Fixture
HTV = H-II Transfer Vehicle
JAXA = Japanese Aerospace Exploration Agency
l = total corridor length
MBS = Mobile Base System
P1 LOIB = Port 1 Lower Inboard
P1 LOOB = Port 1 Lower Outboard
R = range
RVS = Rendezvous Sensor
RWS = Robotic Workstation
S1 LOOB = Starboard 1 Lower Outboard
SpaceX = Space Exploration Technologies
SSRMS = Space Station Robotic Manipulating System
v = vehicle length/size
VV = Visiting Vehicle
VVO = Visiting Vehicle Officer(s)
x = corridor length

I. Introduction

The Automated Vehicles and Orbit Analysis Group (DM35) at the National Aeronautics and Space Administration (NASA) is responsible for performing orbit trajectory analysis on all visiting vehicle operations in the proximity of the International Space Station (ISS). This group has two front room Flight Control Positions: The Visiting Vehicle Officer (VVO) and Automated Rendezvous Officer (ARO). When a Visiting Vehicle (VV) approach is in progress, a system of ISS mounted cameras are used to provide the ISS crew with real time video of the vehicle as it approaches the capture point.

DM35 is primarily concerned, from a video monitoring perspective, with the following Visiting Vehicles: The Japanese Aerospace Exploration Agency's (JAXA) H-II Transfer Vehicle (HTV), Space Exploration Technology Corporation's (SpaceX) Dragon, and Orbital Science Corporation's Cygnus. DM35 has appropriately denoted these

vehicles as "grapploid" Visiting Vehicles because the Space Station Robotic Manipulating System (SSRMS) will grapple with the vehicle's Flight Releasable Grapple Fixture (FRGF) at a particular distance from the ISS prior to the berthing process. Once the robotics team has confirmed a good grapple with the FRGF, the SSRMS will then manipulate the vehicle to the appropriate ISS docking port.

In order to ensure the vehicle approach process runs nominally, the respective owners of each grapploid Visiting Vehicle designed an imaginary three-dimensional corridor in space called the Crew Abort Corridor. The Crew Abort Corridor is a frustum, or a portion of a solid cut by two parallel planes, in this case a truncated pyramid. As a visiting vehicle closes the range between it and the ISS, the cross section of the Crew Abort Corridor decreases exponentially because the area in space for the vehicle to perform a safe abort decreases. The reasoning for this is because the area outside the Crew Abort Corridor violates flight rules for an abort and/or has not been fully analyzed for an abort scenario. In addition to nominal approach trajectory assurance, the Crew Abort Corridor also ensures that the Visiting Vehicle is on the right trajectory for the FRGF to be inside the Capture Volume (CV). The CV is the location in space where the SSRMS can safely grapple the FRGF when the vehicle is in Free Drift mode. The area outside the CV has been deemed unsafe for both vehicle Free Drift and SSRMS grapple. Therefore, it is of the upmost importance that each Visiting Vehicle stays inside the Crew Abort Corridor at all times during the approach/grappling process.

II. Vehicle Approach Monitoring[1]

The ISS crew is responsible for monitoring the VV during its approach to the CV. This is done via the Robotic Workstation (RWS) in the Cupola and/or the backup RWS in the Lab. The RWS has three overhead monitors with live video feed from selected ISS exterior cameras. Each camera has the ability to pan, tilt, and zoom via the RWS Hardware Control Panel. For this vehicle approach monitoring, ISS Mobile Base System (MBS), Starboard 1 Lower Outboard (S1 LOOB), Port 1 Lower Outboard (P1 LOOB), Port 1 Lower Inboard (P1 LOIB), and Lab Cameras can be used in pairs. In addition to providing a live feed of the vehicle during an approach, the RWS monitors also generate overlays from data based on the Visiting Vehicle telemetry. The overlays are as follows[2] (in accordance to Figure 1):

1. Vehicle Telemetry Data
2. Crew Abort Corridor
3. Vehicle Outline
4. Vehicle Strobe Tracker
5. ISS Velocity Vector
6. Nested Corridor

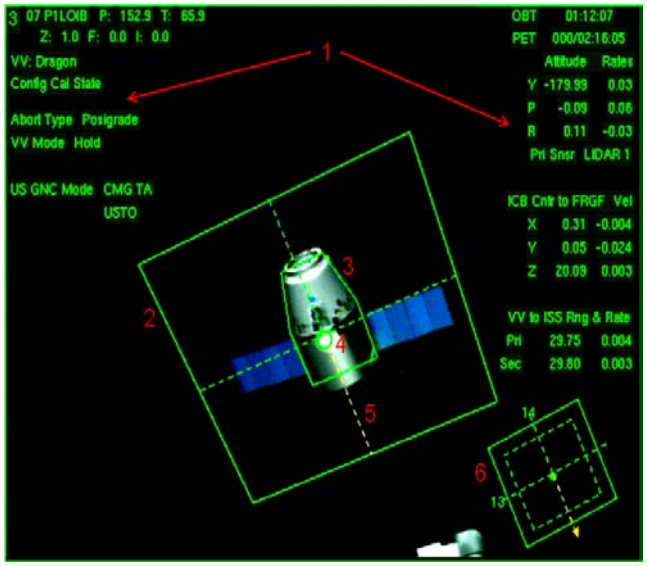

Figure 1. RWS Monitor Screenshot. *Sample of one RWS monitor. Data and overlays based on vehicle telemetry.*

In an ideal vehicular approach, both the vehicle outline and actual vehicle image will be located in the center of the Crew Abort Corridor overlay. As a result of certain known errors, this may not always be the case. These errors include ISS camera biases and offsets, vehicle telemetry errors, or vehicle underperformance. In order for the source of these errors to be ascertained, *both* ISS crew and Mission Control Center (MCC) personnel must analyze the information provided through the RWS images and overlays. The main issue pertaining to this is that MCC has no way of directly seeing what the ISS crew is seeing on the 3 RWS monitors. (Software to duplicate the RWS functionality on the ground is in work but will not be available in time for upcoming VV flights.) There are, however, two indirect procedures which allow MCC to interoperate and analyze the data from the RWS:

1. Direct KU Band Video Feed

Direct KU band video provides MCC with a downlink of the video from the ISS. To view the RWS overlays, an "over-the-shoulder" camera would be mounted inside the Lab which views the RWS monitors. Video would then be down linked from ISS to MCC via KU band video communication wavelengths. There are, however, many

problems associated with this particular approach, one being that scheduling of continuous KU assets is challenging. Secondly, the image quality tends to be poor as visual sharpness and integrity tends be lost while recording a monitor.

2. ISS Crew Calls

The second and more reliable way for MCC personnel to obtain RWS monitor information involves having the ISS crew call down exactly what they are seeing on the space-to-ground communication loop. Calls would then have to be made periodically to monitor the approach and spot any trends of the Visiting Vehicle during the berthing process. In order for this to become feasible, the VVO team devised a concise and reliable way for the crew to describe the images and overlays seen on the RWS monitors. These calls are known as the Block B (Block "Bravo") Crew Calls.

A. Block B Crew Calls

Standard Block B Crew Calls are divided into four distinct and important parts. First, the crew will confirm that the blinking white strobe light located on the VV is inside the Crew Abort Corridor. If it is not, both MCC personnel (particularly the VVOs) and ISS crew must take the necessary steps to ensure crew and vehicle safety. In the second part of the Block B call, the crew compares the physical size of the vehicle to the physical size of the Vehicle Outline overlay. This is done in terms of a percentage increase in size, percent decrease in size, or perfect size match. This is important because the relationship between the on-screen vehicle image and its outline can indentify whether the vehicle is closer or farther than what the telemetry is depicting. In the third and most important part of the Block B call, the ISS crew describes the vehicle's white strobe light position in relation to the strobe tracker overlay, in terms of vehicle length and width. If discrepancies are found they can be attributed to one or more of the following possible errors:

1. The VV is tracking the wrong place (reflector or other object) on ISS structure.
2. The VV has a LIDAR angular bias.
3. The ISS cameras being used for the RWS monitor displays have some sort of biases.

VVOs can use trend monitoring to determine which errors are causing the discrepancies in the third section of each call by analyzing successive Block B calls during the approach. The call in part three compares the vehicle's telemetry to the visual of the vehicle as seen from the RWS. If the approach monitoring relied solely on vehicle telemetry, many unforeseen errors could occur without crew or ground insight. In the fourth and final step in the Block B Crew Call, the crew describes the strobe tracker's location relative to the center of the Crew Abort Corridor, which is also in terms of vehicular length and width.

Vehicle white strobe and strobe tracker overlay offset directions are described in forward, aft, starboard, and port directions. These directions always correspond with the ISS velocity vector (as seen in Figure 1), regardless of the VV's attitude.

After each Block B call, the VVO team is responsible for recording the data, analyzing it, and then taking any necessary action. VVO team members would have to physically write down the data onto paper or enter the data into a computer spreadsheet. Team members would then perform preliminary analysis and angular offset calculations either by hand or via computational calculator. In order to perform trend monitoring, VVO members would then draw the vehicle and the telemetric overlays per the Block B call (if necessary). This process of recording and analyzing the Block B data proved to be overly time consuming and tedious.

III. Design of Visiting Vehicle Software Tool

The main goal of this project was to develop a computer software tool in which MCC personnel, particularly VVOs, can easily input Block B Crew Call data which is voice communicated from the ISS crew members working at the RWS during a vehicle approach. The VVO team member will use this tool for trend spotting, anomaly prediction, and data recording for future use and analysis. The VV tool was developed using Visual Basic for Applications[3] (VBA) and the program interface itself is run using Microsoft Excel.

The VV tool consists of 10 separate Microsoft Excel spreadsheets:

1. "START"
2. "HTV – Cam 1"
3. "HTV – Cam 2"
4. "HTV Data"
5. "Dragon – Cam 1"

6. "Dragon – Cam 2"
7. "Dragon Data"
8. "Cygnus – Cam 1"
9. "Cygnus – Cam 2"
10. "Cygnus Data"

Upon opening the VV tool, each spreadsheet, with exception of "START," will be hidden. On the "START" screen there are three separate command button user forms labeled HTV, Dragon, and Cygnus. The program user will select which Visiting Vehicle will be used for an approach simulation/mission. Once the appropriate command button is activated, the selected vehicle's "Cam - 1" and "Data" spreadsheets become visible and active. The user is then ready to run the program per the given Block B Crew Calls.

A. Crew Abort Corridor Dimension Calculations

In order for the VV tool to best mimic the RWS overlays, the Crew Abort Corridor must appear to be the appropriate length and width at any given point during the approach. Each vehicle's Crew Abort Corridor has set rectilinear dimensions (in meters) per vehicle range from the SSRMS Capture Volume. In addition to these dimensions, angular shifts in the *+x*, *-x*, *+y*, *-y* directions were also available for geometrical calculations[4]. Upon preliminary analysis, it became clear that overall Crew Abort Corridor size increased as VV range increased, which was expected. As shown in Figure 2, Crew Abort Corridor geometric analysis can be used to determine the following:

$$l = x + 2R\tan\theta \quad (1)$$

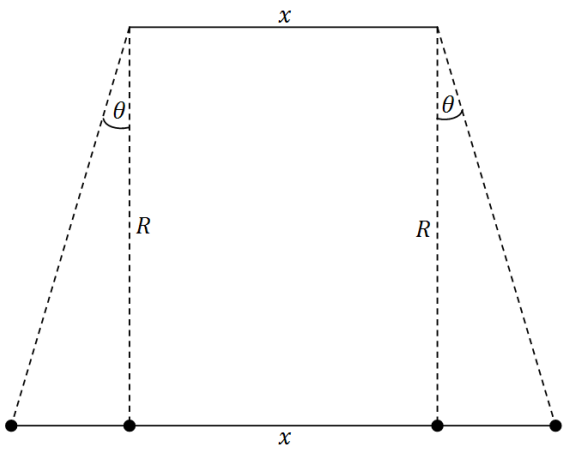

Figure 2. Crew Abort Corridor Geometry. *Where x denotes original corridor length and R denotes vehicle range.*

Equation 1 is used to describe the corridor side length for any Visiting Vehicle at any given range, assuming a symmetric corridor. By implementing Equation (1) into preset vehicle Crew Abort Corridor dimensions, corridor length can easily be calculated.

For program interface simplicity, corridor sizes remain constant as vehicle graphic lengths and widths increase appropriately, creating the illusion that the Crew Abort Corridor is dynamically changing. Known vehicular length values are then divided by Equation (1). Original corridor lengths were then substituted as *x* to yielding a ratio between vehicle length and corridor length. Finally, these ratios were graphed against an array of ranges. Best fit power equations were determined for all three vehicles as a result of this graphical analysis:

$$v = 5.3675 + R^{-.798} \quad (2a)$$

$$v = 3.8953 + R^{-.739} \quad (2b)$$

$$v = 1.5210 + R^{-.757} \quad (2c)$$

Equations 2a, 2b, and 2c all denote the vehicle sizes, *v*, of HTV, Dragon, and Cygnus, respectively. As the range value, *R*, increases, vehicle size decreases appropriately. By incorporating this equation into the program code and multiplying its value by the corridor graphic size, Visiting Vehicle length will be sized as seen on the RWS monitors. Default VV length to with ratios were then added to the program code in order to ensure the vehicle graphic aspect ratio remains constant at any inputted range.

B. Vehicle Angular Offset Calculations[5]

In order for there to be a nominal Visiting Vehicle berthing process, the vehicle must be within the Capture Volume during Free Drift for SSRMS grapple. The CV itself is a three dimensional volume in space located at the end of the Crew Abort Corridor. Due to the fact that the Capture Volume is not a finite point, vehicle offsets from the center of the corridor can be tolerated, to a certain extent. It is of the upmost importance that the VVO team

monitors Block B calls throughout the entire approach to ensure the vehicle is trending towards the correct capture location.

Each ISS camera used during the approach has distinct pan and tilt angular errors which were predetermined via testing. These individual errors are usually eliminated by camera calibration processes prior to Visiting Vehicle approach. In addition to these known camera biases, NASA engineers have also characterized camera biases based on uncontrollable anomalies, which can be seen in Figure 3. The Visiting Vehicle Software Tool has incorporated these know offsets into its coding for Capture Volume analysis.

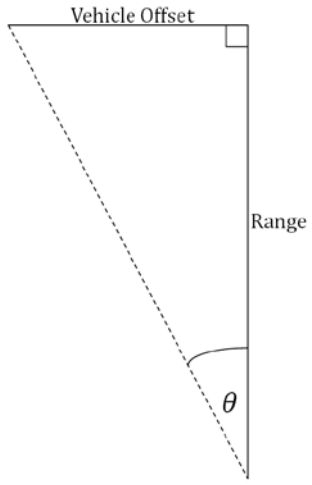

Figure 4. Vehicular Angular Offset.

Certain *vehicular* angular offsets will occur in the event that the white strobe light on the approaching vehicle is not in line with the strobe tracker overlay. For simple analysis these angles can be calculated in the Forward/Aft and Starboard/Port directions. The exact angular offsets can then be calculated because Block B call offsets are in terms of vehicle dimensions, which are known. The direction of the vehicle's shift is perpendicular to the range, creating a right triangle, thus angular offsets can be easily calculated using simple trigonometry (See Figure 4). In the VV Tool, these calculated angular offsets are compared to the known biases from Figure 3 (which have been converted from pan and tilt offsets to Forward/Aft and Starboard/Port directional offsets). The interface will give a warning to the user in the event the calculated angular offset exceeds the Capture Volume limits. With this information, VVO team members can take proper action to ensure the VV will be at an acceptable capture location.

Camera Fixed Biases

S1 LOOB Fixed Bias Pan	+ 2.0 deg
S1 LOOB Fixed Bias Tilt	- 0.2 deg
P1 LOIB Fixed Bias Pan	+ 2.5 deg
P1 LOIB Fixed Bias Tilt	- 1.3 deg
MBS Fixed Bias Pan	- 2.6 deg
MBS Fixed Bias Tilt	+ 0.7 deg
P1 LOOB Fixed Bias Pan	+ 0.6 deg
P1 LOOB Fixed Bias Tilt	- 0.1 deg

Capture Volume Error Sources

ISS Thermal deformations	+/- 0.20 deg
ISS Structural flex	+/- 0.28 deg
ISS Attitude knowledge	+/- 0.50 deg
ISS Attitude control accuracy	+/- 0.80 deg
ISS Mechanical misalignment	+/- 0.96 deg
ISS Margin under USOS control	+/- 0.66 deg
ISS New RWS Quaternion SW Bug	+/- 0.06 deg
Cam Error Range Pan	+/- 2.0 deg
Cam Error Range Tilt	+/- 0.8 deg

Figure 3. Camera Biases and Error Sources

C. Visiting Vehicle Tool Trend Monitoring

An important aspect of the Visiting Vehicle Software is Block B trend monitoring and evaluation. The VV program allows users to view previous Block B Crew Calls throughout the entire approach process. By way of the software tool, the user can easily view previous Block B vehicle images and outlines at will. With this important feature, VVO team members can then determine what errors, if any, are present by way of trend evaluation.

IV. Visiting Vehicle Software Tool Layout

It was determined that the Visiting Vehicle tool must ensure that any user at MCC could generate an image based on the ISS crew Block B call in a quick and concise manner. Additionally, the tool must perform preliminary analysis calculations and analyze trends. Therefore it was designed to have a "user friendly" interface with many various features.

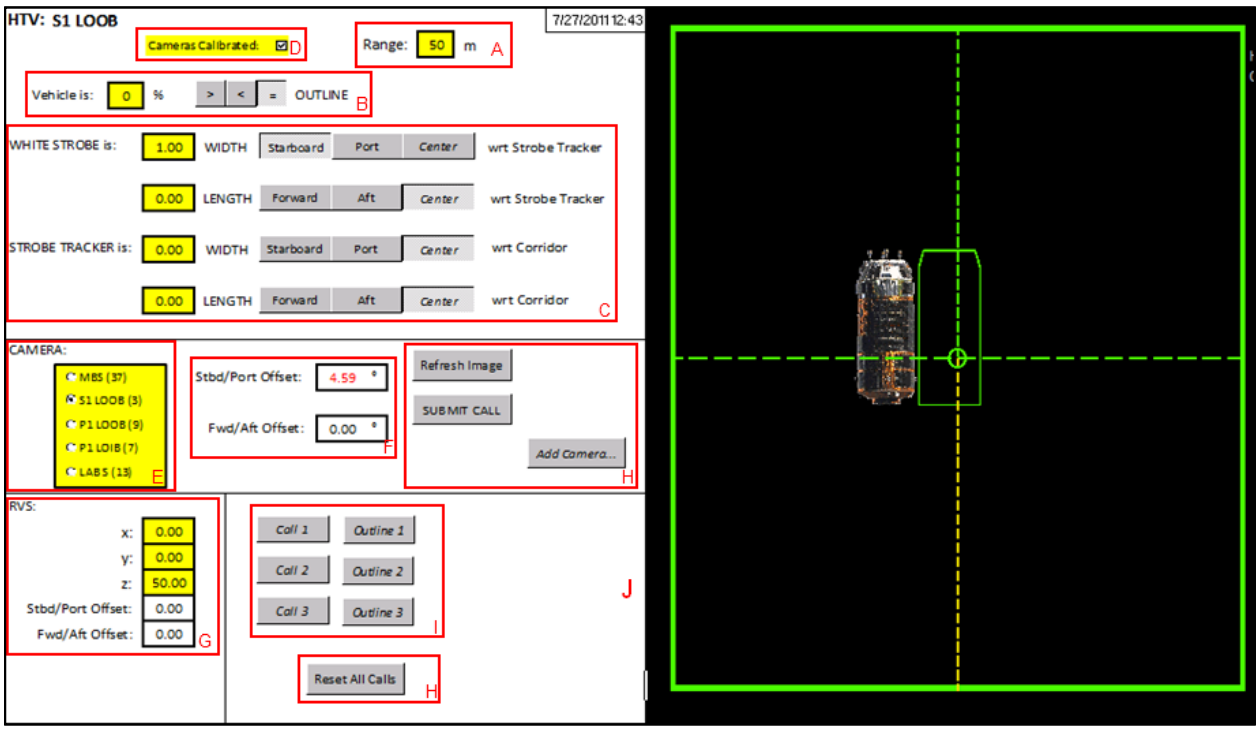

Figure 5. Visiting Vehicle Tool User Interface. *Red outlines and lettering are for reference only and are not included in the actual program user interface. Detailed explanation of the interface design can be found below.*

A. Range Input

Vehicular range from ISS is inputted per Block B Crew Call. Inputted numerical contents are then used for various coded calculations for the VV software tool.

B. Vehicular Outline Input

Per Block B call, the program user has the option to input the appropriate vehicular size with respect to the outline size in terms of a percentage. Program user has the option to enter the numerical percentage value and then select either ">", "<", or "=". The vehicle image will then be sized automatically depending on the size change selection and numerical value inputted.

C. Vehicular Offset Interface

The Vehicular Offset Interface allows the user to input all data associated with the Visiting Vehicle's strobe light and strobe tracker's location. Numerical data is inputted in terms of VV lengths and widths as heard via the Block B call. The interface then allows the user to set the graphic's location by way of Forward/Aft and Starboard/Port directional vectors. If the ISS crew confirms certain parameters of the vehicle white strobe or strobe tracker are centered, then the user also has the option to input this information to the program.

D. Camera Calibration Selection

In the likely event that ISS cameras have been calibrated, the program user has the option to confirm this with the VV software tool. The program will then ignore certain individual angular biases based on the cameras having been calibrated, and conversely incorporate them into the mathematical calculations if they have not been calibrated.

E. Camera Selection

The camera selection box allows the program user to choose the active camera for the current Block B Crew Call. This ensures that the correct uncalibrated angular biases are incorporated into the VV software tool's mathematical calculations.

F. Angular Offsets

Calculated angular offsets are displayed in both the Forward/Aft and Starboard/Port directions. In the event that the vehicle angular offsets violate Capture Volume limits, the actual text in the angle display box will turn red. The threshold in which the program turns this text from standard black to red is governed by the known camera biases and capture volume errors.

G. RVS Telemetry

The user has the option of inputting RVS x, y, and z telemetric values. The software will then auto calculate all the angular offsets and capture volume errors, turning the display text red to indicate RVS capture volume threshold violation.

H. Refreshing Graphics, Exporting Data, Adding Additoinal Cameras, and Resetting the Program

The "Refresh Image" command will automatically generate the images and overlays as seen in the RWS monitors when the program user is satisfied with the inputted data. The "SUBMIT CALL" command button will automatically transfer all data pertaining to the previous Block B Crew Call to the appropriate Visiting Vehicle data sheet for future evaluation. In the event that the ISS crew is noting different visuals in the 2 RWS cameras during a Block B call, there is an option to load a new VV Tool Interface screen for dual camera monitoring. The "Reset All Calls" command button will reset all previous trend monitoring aspects of the software tool in the event that the user would like to start the approach monitoring process over without closing the program.

I. Trend Monitoring

For trend monitoring, the program user has the option of turning on all or any of the previous Block B call graphics and vehicle outlines. Upon doing so, the images will appear in the graphical display.

J. Visiting Vehicle Software Tool Graphical Display

The graphical display mimics the RWS monitors via the Block B Crew Call data inputted into the program user interface.

V. Conclusion

Visiting Vehicle Officers as well as Mission Control personnel need to have efficient means of obtaining data and solving problems as nearly all aspects of every spaceflight mission are time sensitive. Therefore, the development of a Visiting Vehicle Software Tool for HTV, Dragon, and Cygnus approach and grappling to ISS was of the upmost importance. This project, and the rationale behind its development, are perfect examples of why the National Aeronautics and Space Administration strives to perfect the way the crew in space communicates with MCC ground controllers.

One important lesson NASA has learned via all its past endeavors is that there is always room for improvement and innovation. With the Space Shuttle Program coming to an end, NASA is relying on other space agencies and civilian companies for future ISS transportation operations.

The Visiting Vehicle tool is a great success in that it provides the services it was set out to do and was completed in the allotted timeframe. The software tool has passed testing in various simulations and its future looks promising as a valuable asset for use in NASA Mission Control.

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